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Downslope Movement of the Herbicide Hexazinone in the SBS Zone

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Downslope Movement of the Herbicide Hexazinone in the SBS Zone

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SUMMARY

A trial was initiated in the SBS biogeoclimatic zone of British Columbia to investigate the extent and processes of downslope movement of hexazinone, a soil-active, soil-mobile herbicide used in forestry. Three rates and two time periods of application were tested on two soil types near Smithers, B.C. The hexazinone was applied on the top 100 m, and its downslope movement assessed on the lower 40 m by surface and subsurface soil water collected in specially designed troughs located at 7, 15, and 25 m below the last point of application. Hexazinone-sensitive plants, such as rose and aspen, were also used to indicate the extent of downslope movement.

Downslope movement greater than 7 m occurred on all treatments sporadically throughout the year. The greatest amount of movement was associated with spring snowmelt. Most of the downslope movement occurred in the fall of 1987 and the spring of 1988. Concentrations of hexazinone in surface and shallow subsurface flow remained low (0–0.390 ppm) in all treatments. Eighty-two percent of all samples analyzed contained less than 0.050 ppm hexazinone. Results of residue analysis suggest that the fall application on both sites resulted in greater downslope movement than did the spring application.

The downslope vegetation assessments indicated movement up to 50 m on some plots, although the movement path was always confined to a narrow strip (<2–3 m wide). Regulatory agencies agreed that hexazinone, as applied in this trial, had very little potential to cause significant adverse effects to the environment because of the narrow strips affected and the low concentrations found.

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1 INTRODUCTION

Hexazinone, a soil-active, soil-mobile herbicide (trade name Velpar® L), has been in use in the Prince Rupert Forest Region since 1984. Although initial prescriptions for hexazinone were conservative because of the lack of local experience with its use, continued vegetation assessments to evaluate crop tree tolerance and efficacy on target species rapidly increased the bank of local knowledge about the herbicide. These assessments, however, highlighted a potentially problematic characteristic of hexazinone, namely, its high mobility in soils of the Prince Rupert Forest Region under certain conditions.

Velpar® L is registered in British Columbia for use as a broadcast spray and for spotgun application directly to the soil surface. The chemistry of the herbicide is such that it is weakly adsorbed to soil particles. It is also highly water soluble and thus mobile within or over the soil matrix (WSSA 1983). This mobility and weak adsorption are what facilitate access and uptake of the herbicide by plants. Although the herbicide was designed to move only a few metres from its spot of application, several cases of movement much greater than that (up to 150 m) have been documented in the Prince Rupert Forest Region.[1]

Hexazinone is transported predominantly in the aqueous phase, moving in the soil both as overland flow and interflow (Ghassemi *et al.* 1982; Neary *et al.* 1983; Bouchard *et al.* 1985). Initial experience with Velpar® L in the Prince Rupert Forest Region indicated that the most critical off-site problems were associated with application of the herbicide on frozen or compacted soils (skid trails and roads) and in small gullies and depressions. However, at one research site in the Region where sampling wells had been installed (J. Pollack, pers. comm., 1986), and in several cases cited in the literature (Neary *et al.* 1983; Bouchard *et al.* 1985), the major pathway for hexazinone movement in the soil was below surface flow (i.e., interflow). Thus, it became questionable whether excess movement of hexazinone was associated solely with compacted soils, and whether movement within the soil matrix might also be an important process.

Because of the occurrences of downslope movement of hexazinone in the Prince Rupert Forest Region, environmental concerns with the herbicide's use were identified. Understanding the processes that cause the movement, and knowing how much movement might be expected under specified environmental conditions, became important research objectives. The concerns were mostly over how the uncontrolled movement of the herbicide might damage streamside vegetation in a pesticide-free zone, or browse species in wildlife habitat. Contamination of fish-bearing streams was of lesser concern because of the relatively low toxicity of the herbicide (for trout, an LC_{50} of about 870 ppm).

The high water solubility (3.3%) of hexazinone and its low adsorption characteristics make it susceptible to off-site movement in storm run-off, snowmelt and leaching (Neary *et al.* 1983). The compound has been placed in class 4 of the Helling and Turner (Helling 1971) mobility classification scheme (i.e., high mobility) (WSSA 1983). The mobility of hexazinone decreases with the increase in clay and organic matter content of a soil (Ghassemi *et al.* 1982). With excessive amounts of organic matter, the herbicide can bind too tightly and consequently lose its efficacy. Thus, a knowledge of the soil characteristics is important if proper prescriptions are to be made, both to reduce off-site movement and to allow greatest efficacy.

Rates of application and timing of application are also critical factors in prescribing the use of Velpar® L. Several different application rates and methods have been tried in the Prince Rupert Forest Region, including: spotgun (4–8 mL/spot), speargun, and broadcast spray. Movement of the herbicide has been documented for each of these spray techniques. Timing trials of Velpar® L were also done in the Prince Rupert Forest Region, with the herbicide being applied in both the spring and fall. Both of these application periods resulted in movement of the herbicide downslope from the treated area. However, the fall application generated the most concern. The occurrence of more rain in the fall, the absence of uptake of the herbicide by plants during the dormant season, the low biological activity in the soils during winter, and the snowmelt and run-off in the spring were all identified as potential causes of greater movement associated with fall applications.

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1 B.C. Forest Service, Smithers, B.C. Unpublished operational reports.

Guidelines for forestry applications of Velpar® L in British Columbia have been developed by B.C. Forest Service Silviculture and Protection staff in consultation with the B.C. Ministry of Environment. However, several questions on the processes that induce movement of hexazinone in the SBS zone needed to be answered so that silviculturists could refine their ability to prescribe Velpar® L as an environmentally safe herbicide. These questions included:

- Is movement of the herbicide within the soil matrix important, or need we be concerned only with overland flow?
- Is vertical leaching important?
- To what extent does the thickness of the humus layer influence mobility, both for off-site movement and efficacy of the herbicide?
- What amount of water (rain, snowmelt) induces substantial downslope movement?
- What role does soil infiltration rate (structure and texture of the soil) have on off-site movement?
- Which application method (spotgun vs. speargun) and rates (mL/spot) produce the least movement for a particular environment and soil?
- What role do frozen soils play in the downslope movement of the herbicide?

2 OBJECTIVES

The objectives of the project were:

1. to determine the extent of downslope movement of hexazinone used under several different application regimes; and
2. to study and describe the processes that induce surface and sub-surface movement of hexazinone.

3 STUDY AREA

To compare six different application regimes of Velpar® L on soils with different depths of organic matter, sites were selected from plots located in the SBSmk and SBSmc zones of the Bulkley, Lakes and Morice Forest Districts.

Two sites were chosen, each having the following criteria:

- fine to medium textured till
- a constant slope of about 150 m in length
- a slope gradient of 12–15%
- a southerly aspect
- the presence of Velpar®-sensitive species in sufficient quantity for damage surveys.

The main variables that differentiated the two sites were soil moisture regime, precipitation regime, and depth of organic matter. The drier of the two sites was located near Houston, B.C. (SBSmk/01) (site 1; Fig. 1). The wetter site was located near Moricetown, B.C. (SBSmc/06) (site 2; Fig. 1).

FIGURE 1. Location of research sites.

The drier site, which we refer to as the Swiss Fire site, is a mesic site that was dominated by lodgepole pine (*Pinus contorta* var. *latifolia*) with a minor component of aspen (*Populus tremuloides*) and spruce (*Picea glauca* x *engelmannii*). In the spring of 1983, the site was burned by a wildfire, after which the Forest Service directed the forest companies to begin salvage operations. The experimental site was clearcut in 1984 and the slash was piled and burned. The site was left for natural regeneration by lodgepole pine. Invasion of aspen onto the site was perceived as a potential problem. Velpar® L was considered to be a viable tool for controlling aspen on these sites, but because of the perceived problems with downslope movement and the lack of knowledge of the efficacy and crop tree tolerance of the herbicide, foresters hesitated prescribing it.

The wetter site (SBSmc/06), which we refer to as the Gramophone Creek site, is moister and richer than mesic and identified as a Moist-Thimbleberry-Forb site. The site was originally dominated by white spruce with minor components of balsam (*Abies lasiocarpa*), lodgepole pine, and cottonwood (*Populus balsamifera* ssp. *trichocarpa*). The coniferous trees were logged in 1976, followed by spot burning in 1978 which left a tall overstory of cottonwood. The site was mechanically prepared by a Bräcke scarifier in 1985 and planted in 1986 with lodgepole pine intermixed with some natural spruce regeneration. A herbicide treatment using Velpar® L was targeted for this site to control cottonwood and thimbleberry (*Rubus parviflorus*). The physical features of the site, the deeper layer of organic matter, and the proposed Velpar® L treatment made it a good candidate for this research trial.

4 METHODS

4.1 Plot Layout and Treatments

At each of the two sites, 12 adjacent 30 x 140 m plots were layed out along a 15% slope. Hexazinone was applied on the top 100 m, and the assessment of downslope movement was done on the lower 40 m. The application of hexazinone in the undiluted liquid formulation (Velpar® L) was applied directly to the soil at three rates.

Each of the three rates was tested in a spring application (May 25 and 26, 1987) and a fall application (October 6 and 7, 1987) on each of the two soil/climate types. This yielded a total of 12 treatments (3 rates x 2 application dates x 2 soils). Each treatment was replicated for a total of 24 plots. The layout of these plots are presented in Figures 2 and 3. Table 1 details the six treatments that were done at each site.

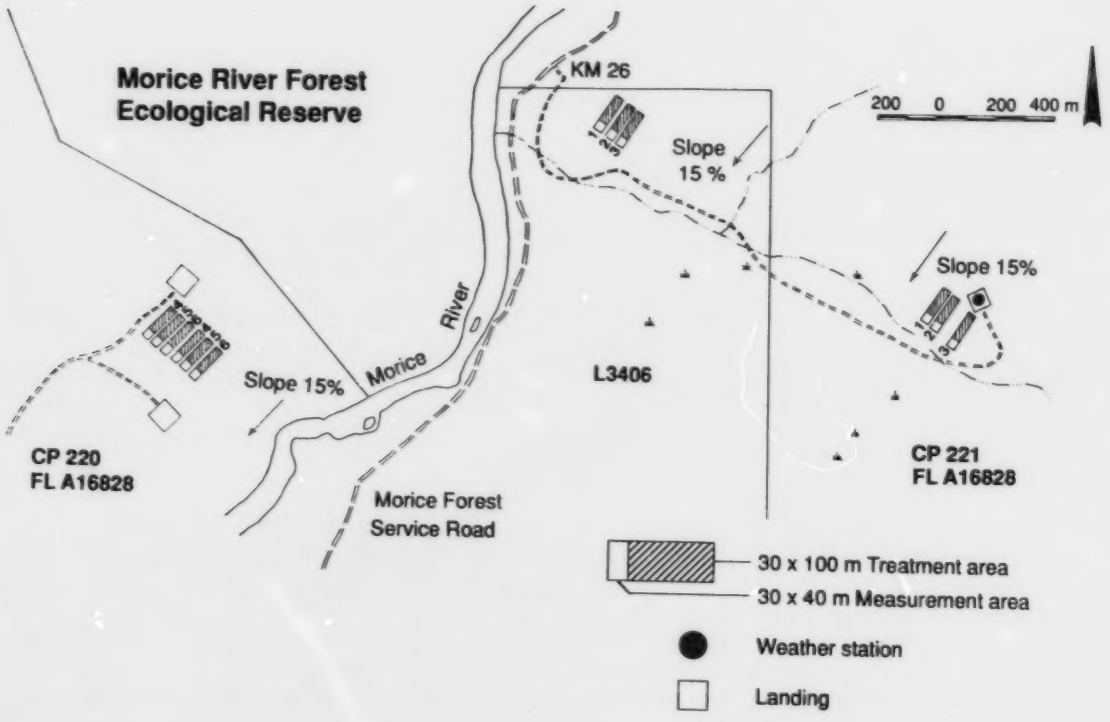

FIGURE 2. Location of treatments: site 1, Swiss Fire.

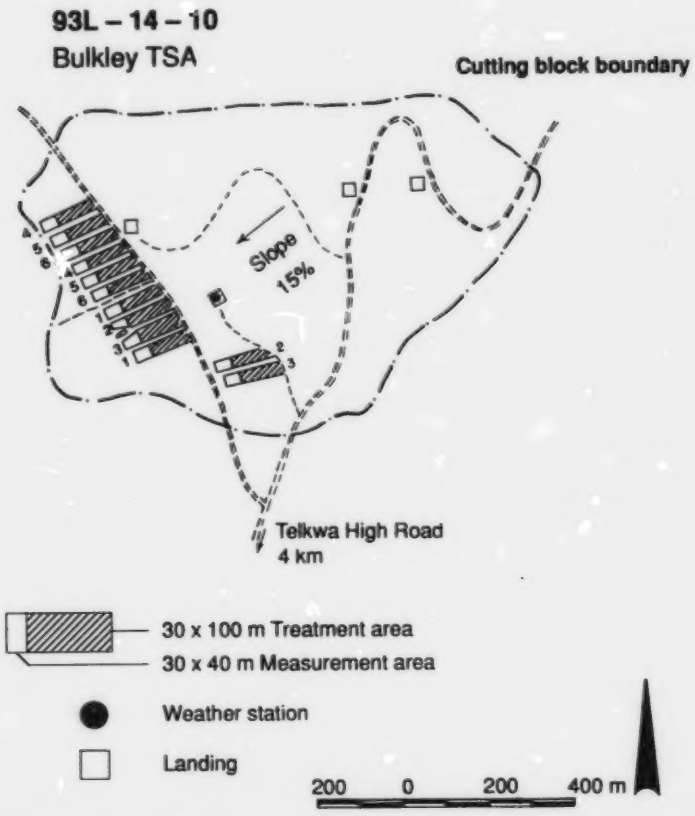

FIGURE 3. Location of treatments: site 2, Gramophone Creek.

TABLE 1. The six Velpar® L treatments

Treatment	Application period	Application method, volume and rate	Referred to in text as:
1	Spring	Spotgun: 4 mL/spot; spacing: 1.5 x 1.5 m; 17.6 L/ha of Velpar® L, 4.2 kg a.i./ha	4 mL/spot
2	Spring	Spotgun: 2 mL/spot; spacing: 1.0 x 1.0 m; 20 L/ha of Velpar® L, 4.8 kg a.i./ha	2 mL/spot
3	Spring	Speargun: 6 mL/spot; spacing: 2 x 2 m; 15 L/ha of Velpar® L, 3.6 kg a.i./ha	6 mL/spot
4	Fall	same as 1	4 mL/spot
5	Fall	same as 2	2 mL/spot
6	Fall	same as 3	6 mL/spot

The herbicide was applied with a spotgun, to which a soil injection spear could be attached (Figs. 4 and 5). The spear was used for all the 6 mL/spot treatments. Velpar® L spots were applied to avoid compacted surfaces, ditches, gullies, and obvious intermittent streambeds.

4.2 Climate Monitoring

On both sites, an automated weather station was installed to measure the climate variables that are critical to movement of hexazinone. Water delivery to the soil was evaluated with a recording rain gauge and a snowmelt lysimeter. Soil temperature, air temperature, relative humidity, and incoming solar radiation were also measured. The climate information was monitored continuously with on-site dataloggers, and the sites were visited monthly for data retrieval and snow surveys. The on-site weather stations were operational from November 1986 to mid-summer 1989. Location of the weather stations are identified on Figures 2 and 3.

4.3 Soil Characteristics

Three soil samples were collected from each of the 24 plots to describe their physical properties. At each sampling location, data on depth of organic matter, hand texturing, and coarse fragment content were collected. Soil moisture was measured periodically with the use of gypsum soil moisture blocks buried at two depths at the three locations for each of the 24 plots.

4.4 Measurements of Downslope Movement

We used two methods to evaluate the extent of downslope movement of hexazinone within each treatment area. These were: 1) a survey of indicator plants for downslope damage; and 2) a sampling of hexazinone concentrations in soil water.

FIGURE 4. Spotgun and adjustable gauge.

FIGURE 5. Spotgun and spearhead attachment.

4.4.1 Survey of indicator plants

Plants sensitive to hexazinone, such as aspen, fireweed, rose, thimbleberry and willow (indicator plants) were surveyed once a month during the 1987 and 1988 growing seasons to assess herbicide damage in the non-sprayed zone of the plot. The surveyor looked for characteristic Velpar® L damage such as: necrotic leaves, necrotic branch tips, and stem die-back. Damaged plants were identified by species and the degree and nature of damage (high, medium, low). The plant or group of plants damaged were tagged, dated and photographed to keep a record and to permit comparisons of damage through time.

4.4.2 Soil water sampling

Soil water samples were collected below the soil surface at depths of 5 and 20 cm at each of three distances (7, 15 and 25 m), downslope of the herbicide application area (Fig. 6). These custom-designed troughs were constructed of PVC sewer pipe 10 cm in diameter and 1.5 m in length and perforated over the whole length for a 5 cm wide section of the circumference (Fig. 7). The troughs were placed horizontally at the two depths in a shallow 1.5 m long trench dug across the slope. The water was collected in a vertical section of sewer pipe located at the end of the trough. The shallow troughs sampled overland flow and shallow interflow; the deeper troughs sampled deeper interflow. A total of 144 collectors were installed at the two sites (2 depths x 3 downslope distances x 3 rates x 2 periods x 2 sites x 2 replications).

Soil water sampling began in the summer of 1987 and continued through to the spring of 1989. The intention was to collect water samples from every trough at every site visit, but in many cases throughout the 2-year sampling period, troughs were either dry or did not have sufficient water for sampling. This is the reason for the uneven sample sizes reported in Table 2. The troughs and collectors were pumped dry after each sample collection to ensure that each sample was discrete and independent of the previous one. The quantity of water pumped from each collector was noted. The collected water samples were

immediately taken to the office where they were frozen and details of the sample recorded in a log book. The samples were grouped into five sampling periods: summer 1987, fall 1987, spring 1988, fall 1988, and spring 1989.

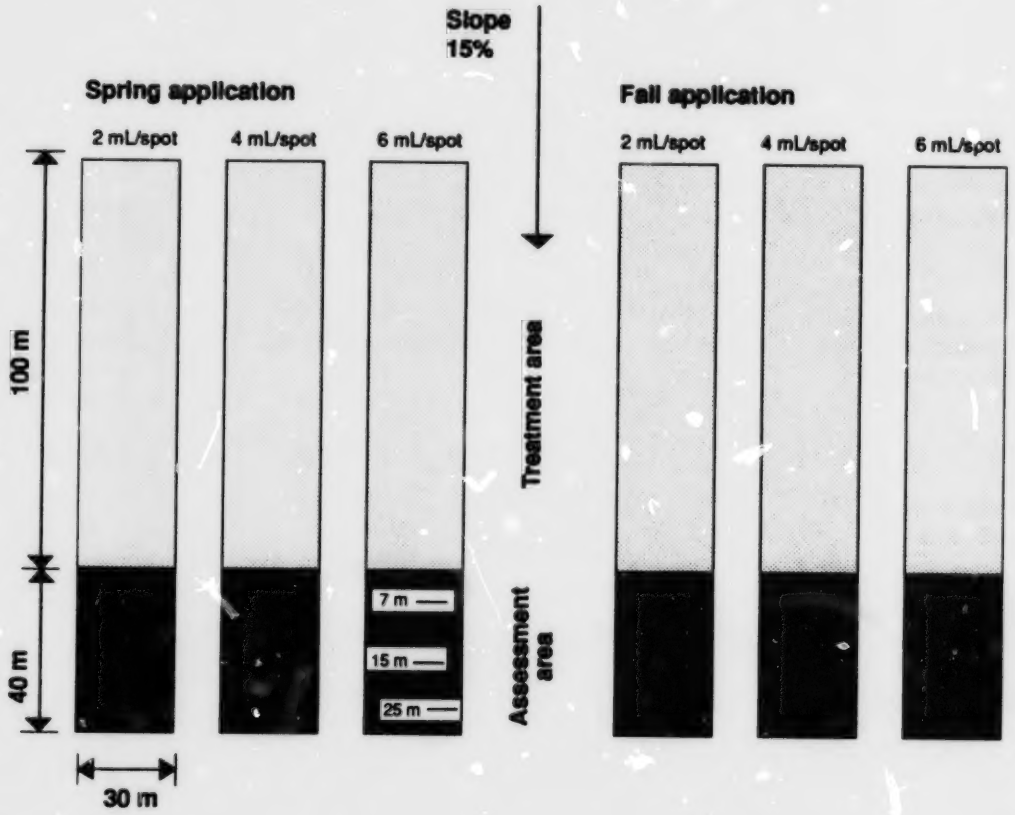

FIGURE 6. Layout of experiment and location of collector troughs.

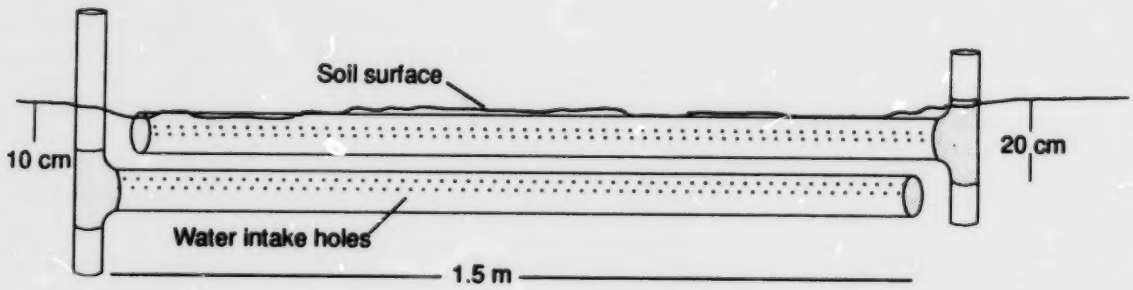

FIGURE 7. Design of collector troughs.

Selection of water samples for chemical analysis

Because of the high cost of chemical analysis, not all samples collected could be analysed, and thus sub-sampling was necessary. The sub-sampling procedure was designed first to detect the occurrence of downslope movement and then to concentrate the analysis on the plots that had the greatest amount of movement. Between June 1987 and May 1989, six batches of approximately 40 samples per batch were sent for chemical analysis. The samples chosen for the first two batches were selected to represent all treatments, the deep and shallow troughs, and the three downslope sampling distances. Each of the four subsequent batches of samples was selected according to the accumulated information provided by the previous samples. Thus, the sub-sampling was not a random process, and was not designed to compare mean values. Of greater interest than the means was the frequency of occurrence of residue levels above a certain level (e.g., Were there more samples with residue levels greater than 0.050 ppm produced from the fall application compared to the spring application?). Consequently, statistical analysis of the means was not appropriate for this experiment. The means for each treatment are reported, but statistical inferences are not made. Rather, the discussion concentrates on the relative frequency of occurrence of the residue samples in one of four classes. Table 2 documents the number of samples that were collected and analysed from each treatment.

TABLE 2. Number of samples collected and analysed

Site	Season	Application type	Number of samples collected	Number of samples analysed
Swiss Fire	Spring	2 mL/spot	47	18
		4 mL/spot	66	17
		6 mL/spot	59	19
	Fall	2 mL/spot	53	22
		4 mL/spot	54	20
		6 mL/spot	54	20
Gramophone Creek	Spring	2 mL/spot	47	18
		4 mL/spot	56	16
		6 mL/spot	49	22
	Fall	2 mL/spot	33	15
		4 mL/spot	33	15
		6 mL/spot	42	24

Chemical analysis of water samples

The water samples were analysed for the presence of hexazinone and metabolites "A" and "B" by Graeme Masson of the Industrial Chemistry Division, British Columbia Research Corporation in Vancouver. The samples were solvent-extracted and analysed on a Hewlett Packard 5890 gas liquid chromatograph equipped with split/splitless injector, nitrogen/phosphorus specific detector, and a 30 m x 0.30 mm i.d. DB-5 capillary column.

The quality control used in this project consisted of:

- a range of standards analysed before, during, and after each batch of samples, with the standards selected to bracket the sample results;
- reagent blanks carried through the complete procedure with every batch; and
- spike and recoveries done on two randomly selected samples in each of the batches.

5 RESULTS AND DISCUSSION

5.1 Atmospheric Climate

5.1.1 Gramophone Creek

Rainfall and air temperature data for 1987 and 1988 are presented in Figure 8. The total rainfall for the period May to December was 369 mm and 407 mm for 1987 and 1988, respectively. Rainfall was generally well distributed throughout the year, with no major drought periods. Large rainfall events occurred in September of both years.

In both 1987 and 1988, the snowmelt period began in early March when average daily air temperatures rose above 0°C. The most intense snowmelt period occurred between March 20 and April 13 in both years. This suggests that optimal soil moisture conditions for a spring application of Velpar® L on this site would be late April-early May. Spring run-off would be over, yet the soils would still be moist enough to ensure good efficacy of the herbicide.

5.1.2 Swiss Fire

Total rainfall for each of the years was 226 mm and 317 mm, respectively, which is substantially less than the rainfall recorded at Gramophone Creek. Figure 9 shows the weekly distribution of rainfall. It is evident from these data that 1987 was a much drier year than 1988, having experienced some obvious dry spells during the summer and fall. Average weekly air temperatures are also presented in Figure 9.

In 1987, the peak of snowmelt at the Swiss Fire occurred over the short period between March 1 and March 15, which was 2 weeks earlier than at Gramophone Creek. In 1988, all climate data were lost between March 11 and April 13, the period when snowmelt occurred. The lesser precipitation at this site and the earlier snowmelt suggest that spring applications of Velpar® L should be completed by the end of April to avoid dry soils.

5.2 Soils

5.2.1 Soil texture

The soils of Gramophone Creek are Brunisols derived from moderately fine textured unsorted glacial till. Of the 36 soil samples collected at this site, 22 were hand-textured as being a loam, 3 as silt loams, 7 as silt clays, and 4 as fine sandy loams. The samples were run through a 2-mm sieve, yielding an average coarse fragment content of 46%. The depth of organic matter at Gramophone Creek varied from 1 cm to 17 cm with an average depth of 8 cm (Table 3).

The soils at the Swiss Fire site were also a fine textured Brunisol derived from unsorted glacial till. However, they were finer and contained a lower percentage of coarse fragment content than the soils at Gramophone Creek. As well, they were covered with a discontinuous and much thinner layer of organic matter. The soil characteristics are summarized in Table 3.

TABLE 3. Soil characteristics of the two sites

Soil characteristics	Gramophone Creek	Swiss Fire
Mean depth (range) of organic matter	8 cm (1–17 cm)	2 cm (0–5 cm)
Mean (range) % coarse fragment content	46% (23–73%)	35% (23–75%)
Mean texture	loam	silt loam

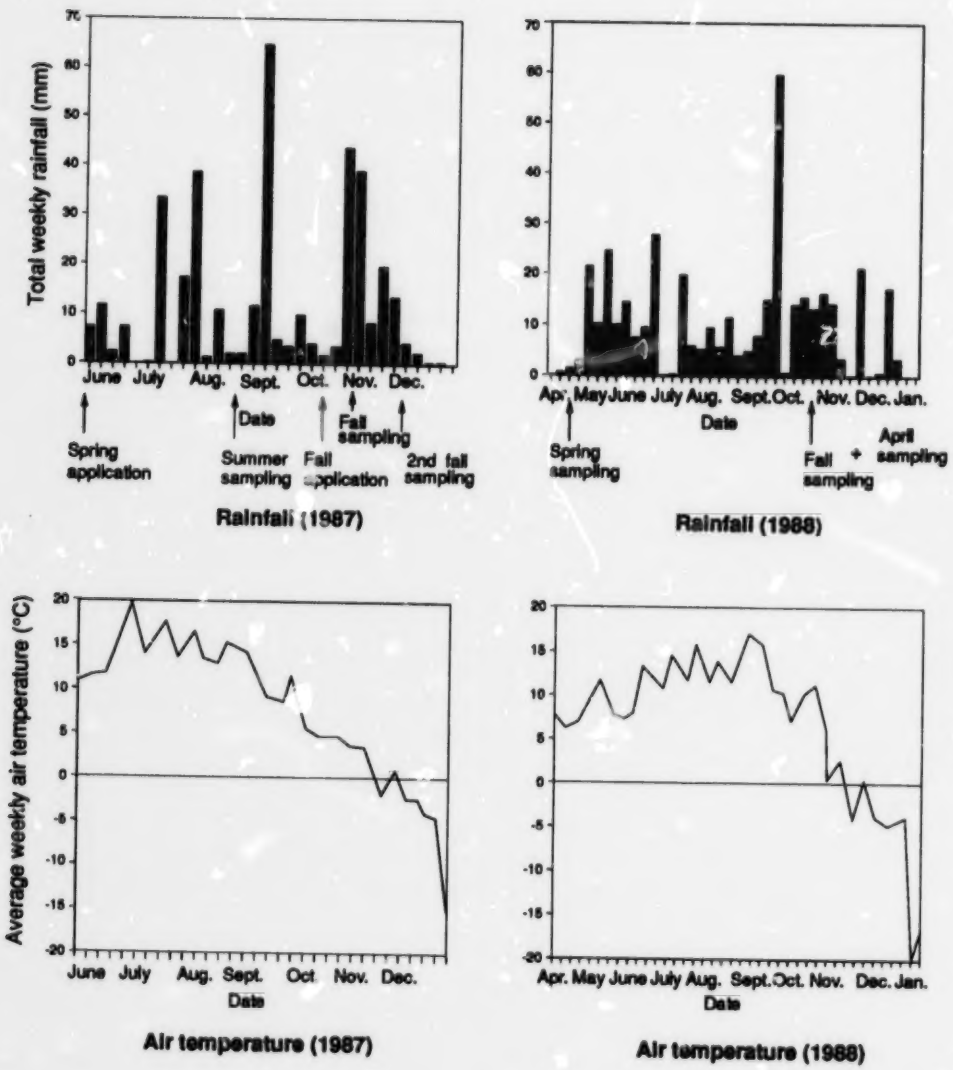

FIGURE 8. Rainfall and air temperature regimes, Gramophone Creek.

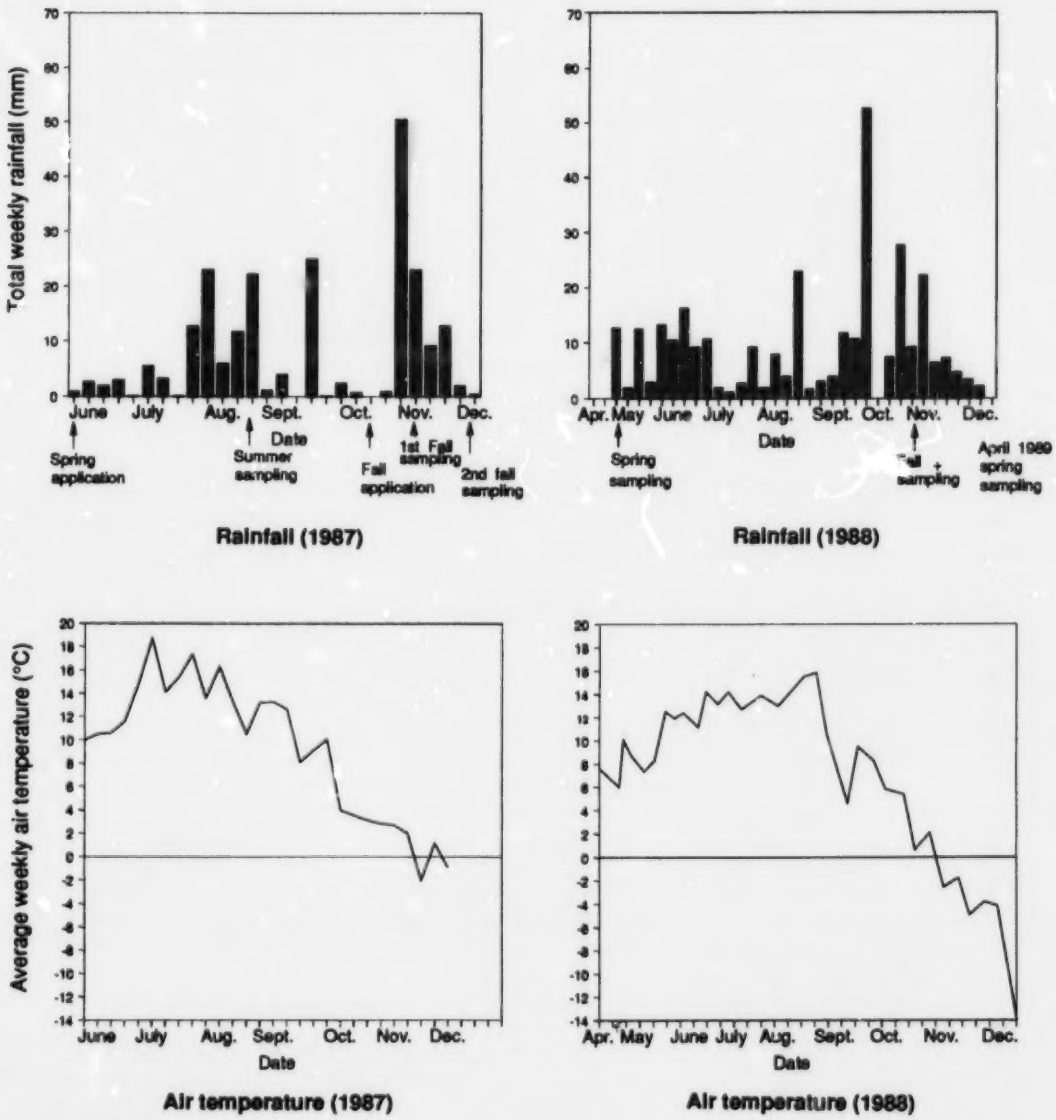

FIGURE 9. Rainfall and temperature regimes, Swiss Fire.

5.2.2 Soil moisture regime

In response to the low precipitation during June and July of 1987, soils at both sites dried out. The driest soils occurred at the Swiss Fire site, with the maximum soil water tension reaching 5 bars (Fig. 10). During the 1987 growing season, soil moisture was generally higher at the Gramophone Creek site. This is reasonable considering the higher rainfall that was recorded there. Rainfall at both sites was more frequent and in greater quantities during the early growing season of 1988 than during that of 1987. Consequently, the soils did not dry out as much in 1988 as they did in 1987, with the 1988 maximum soil water tension being only 2 bars (Fig. 10).

5.2.3 Soil temperature regime

Annual soil temperature regimes were similar at both sites. By late September 1987, temperatures at the surface of the soil started to dip below 0°C, while temperatures at 10 cm depth remained at about 6 or 7°C. By mid-November, snow began to accumulate on the ground and the daily fluctuations of soil temperature (both at the surface and at depth) were substantially dampened. Throughout both the winters of 1987/88 and 1988/89, surface temperatures generally dropped only a few degrees below 0°C, while temperatures at 10 cm depth remained between 0.5 and 1.5°C. When air temperatures dropped below - 25°C, soil surface temperatures dropped to lows of about -7°C, but soil temperatures at 10 cm dropped only very slightly below 0°C.

In 1987 and 1988, snow disappeared from both sites during the first week of April. A steady rise in soil temperature followed, reaching a maximum in August. During July and August, surface temperatures averaged about 16–17°C at Gramophone Creek and a few degrees warmer at Swiss Fire. Soil temperatures at 10 cm depth averaged about 10–12°C at both sites. From September to November, soil temperatures decreased steadily until the snow arrived in mid-November, at which time surface temperatures dipped below freezing and temperatures at 10 cm depth stabilized between 0.5 and 1.5°C.

5.3 Downslope Movement of Hexazinone

5.3.1 Indicator plants

Plant damage, the damage ascribed to hexazinone effects as identified by the surveyor (see Section 4.4.1), was observed in numerous plots. Within the assessment area, most of the plant damage occurred within 5 m downslope of the treatment area. This degree of movement was expected because of the inherent mobility of the herbicide. In several cases, however, hexazinone-damaged plants were observed at distances up to 60 m downslope of the last point of application. The movement path was always confined to a narrow strip of less than 2–3 m wide. Never did we see anything that resembled a curtain effect, where plants would be damaged evenly over a 20–30 m wide swath. Instead, plants were affected along preferential pathways of downslope water movement. Appendix 1 documents the observations made of hexazinone-damaged plants at distances greater than 5 m for each of the 24 plots.

Of the four treatment/site combinations, the Swiss Fire fall treatment was the one that had the most widespread visual evidence of downslope movement.

5.3.2 Hexazinone residues in soil water

Over a 3-year period (1987-1989), a total of 593 samples were collected from the 144 collection troughs located at the two sites. The amount of hexazinone residue and metabolites "A" and "B" were determined for 226 of these samples. Results ranged from no detectable residues to a high of 0.390 ppm (mg/L). The presence of metabolites "A" and "B" remained below detection limits in all of the 226 samples analysed.

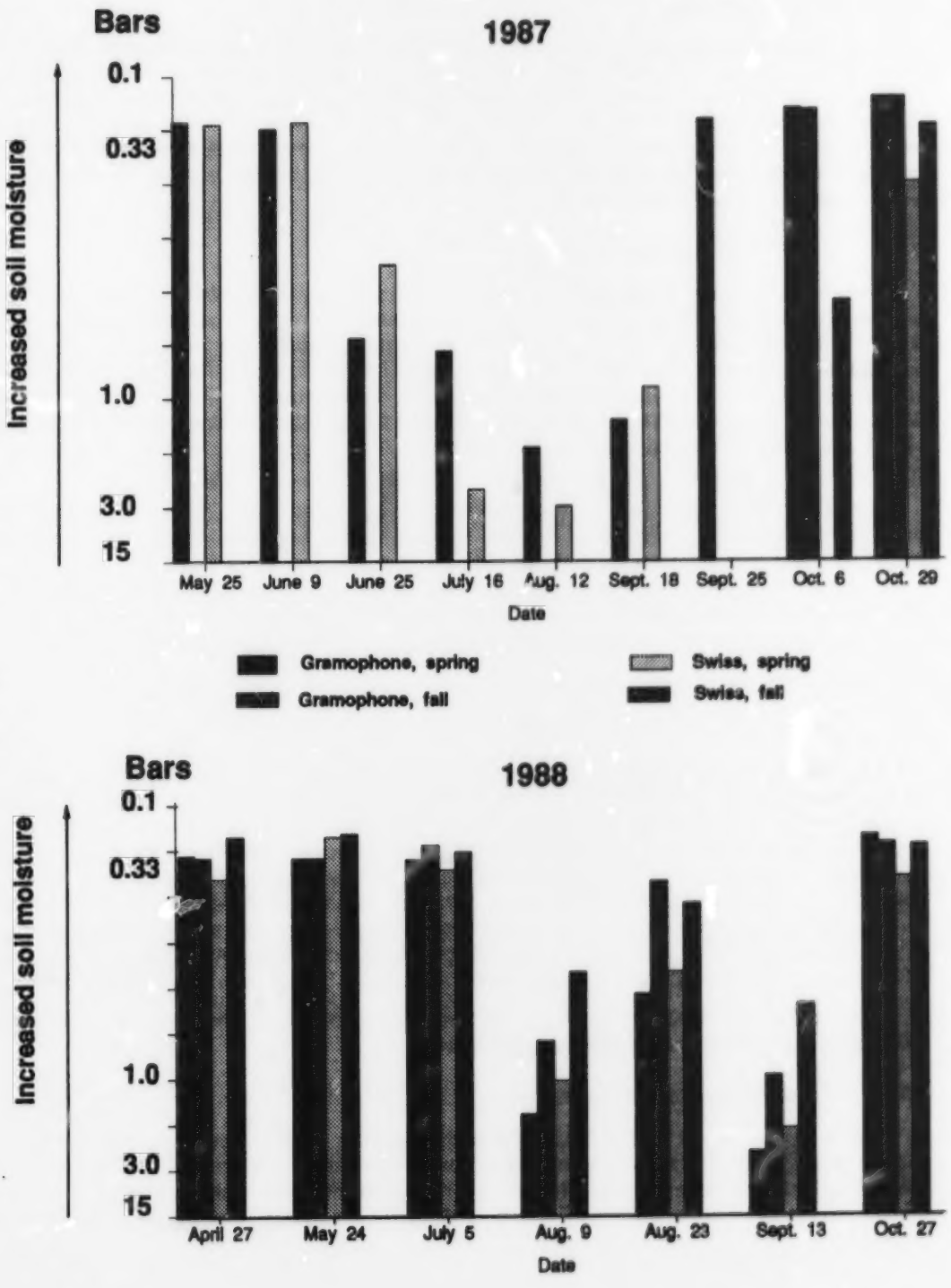

FIGURE 10. Soil moisture regimes at both sites.

Movement at different soil depths

Soil water was collected at two soil depths. The samples collected from the surface troughs (5 cm depth) are identified as "surface" samples; those collected in the deep troughs (20 cm depth) are identified as "deep" samples. In the first two batches of samples sent for chemical analysis, only 18% of the surface samples contained any detectable hexazinone residues, while 65% of the deep samples contained detectable levels. These early results suggested that movement of hexazinone occurred predominantly through sub-surface saturated flow and not as overland flow. Consequently, we decided to analyse more deep samples (n=165) than surface samples (n=61).

In all sampling periods combined, only 26% of the surface samples contained detectable levels of residue. However, in the spring of 1988, 93% of the analysed surface samples contained detectable levels. This suggests that any movement of hexazinone over the soil surface (overland flow) occurs predominantly during the first spring after application. The mean concentration of these surface samples, collected in the spring of 1988, was 0.009 ppm for the spring application and 0.057 ppm for the fall application.

Effects of treatment

Mean levels of hexazinone residue were calculated for each of the 12 treatments. These means incorporate the three downslope distances, the two depths, and the five sampling periods (Table 4). Also included in Table 4 is the relative distribution of samples within each one of four residue level classes.

TABLE 4. Mean residue values by treatment

		Frequency of occurrence by residue level class				
Treatment (type, volume, rate)	**Mean residue in ppm (no. of samples)**	**Below detection limit < 0.010 ppm**	**0.010–0.050 ppm**	**0.051–0.100 ppm**	**Greater than 0.101 ppm**	**Max. residue in ppm**
Gramophone, fall						
2 mL/spot	0.020 (n=15)	67%	20%	13%	0%	0.100
4 mL/spot	0.019 (n=15)	33%	60%	7%	0%	0.054
6 mL/spot	0.049 (n=24)	33%	37%	17%	13%	0.390
Gramophone, spring						
2 mL/spot	0.023 (n=18)	44%	33%	5.5%	5.5%	0.230
4 mL/spot	0.011 (n=16)	50%	50%	0%	0%	0.031
6 mL/spot	0.023 (n=22)	41%	45%	9%	4%	0.160
Swiss, fall						
2 mL/spot	0.044 (n=22)	41%	18%	32%	9%	0.210
4 mL/spot	0.033 (n=20)	38%	48%	5%	9%	0.184
6 mL/spot	0.028 (n=20)	30%	40%	30%	0%	0.088
Swiss, spring						
2 mL/spot	0.023 (n=18)	44%	39%	11%	5.5%	0.180
4 mL/spot	0.025 (n=17)	64%	24%	0%	12%	0.200
6 mL/spot	0.026 (n=19)	54%	24%	11%	11%	0.148

Three main aspects of the data presented in Table 4 should be emphasized. First, the means for all treatments are low. Second, most of the samples (82%) are distributed in the two lower classes (i.e., residue levels less than 0.050 ppm). Third, because all means are similar, we can infer that the different treatments did not produce substantial differences in the amount of downslope movement. An exception to this last point could be the two Swiss fall treatments (2 mL and 6 mL) which have a substantially higher occurrence of samples in the 0.05–0.100 ppm class than do the other treatments.

The data were subsequently lumped so that the differences could be investigated in the amount of movement between site and season of application only, without considering rate of application (Table 5).

Although the mean level of residue remains small for all site/season combinations, a trend in the means is apparent. For both sites, the fall application has a higher mean and thus appears to have produced the greatest amount of downslope movement. Also, in both fall treatments the relative occurrence of samples in the 0.051–0.100 ppm class is substantially greater than in the spring treatments (Table 5). This is probably due to a combination of (1) the large amount of snowmelt run-off that occurs in the spring following application of hexazinone and (2) the limited uptake of hexazinone during the winter by the dormant plants — both processes of which result in more downslope movement. The occurrence of samples in the highest class (i.e., >0.101 ppm) is low for all site/season combinations.

The data were once again lumped, combining the fall and spring data for each of the two sites, so that the effect of the site on downslope movement could be studied (Table 6). Again, the difference between the means is not very large. However, the Swiss Fire site does have a mean that is greater than that for the Gramophone site. The percentage of samples in the 0.051–0.100 ppm class is also greater for the Swiss Fire site. This apparent greater amount of movement at that site was probably a result of the thin layer of organic matter covering the soil there.

TABLE 5. Mean residue values by site and season of application

Treatment	Mean residue in ppm (no. of samples)	Frequency of occurrence by residue level class				
		Below detection limit < 0.010 ppm	0.010–0.050 ppm	0.051–0.100 ppm	Greater than 0.101 ppm	Max. residue in ppm
Gramophone, fall	0.030 (53)	41%	41%	13%	5%	0.390
Gramophone, spring	0.019 (56)	48%	45%	3.5%	3.5%	0.230
Swiss, fall	0.035 (63)	37%	35%	22%	6%	0.210
Swiss, spring	0.025 (54)	55%	28%	7.5%	9.5%	0.200

TABLE 6. Mean residue values by site

Site	Mean residue in ppm (no. of samples)	Frequency of occurrence by residue level class				
		Below detection limit < 0.010 ppm	0.010–0.050 ppm	0.051–0.100 ppm	Greater than 0.101 ppm	Max. residue in ppm
Gramophone Creek	0.024 (110)	45%	42%	8%	5%	0.390
Swiss Fire	0.030 (116)	45%	32%	15.5%	7.5%	0.210

Lumping all data by season of application produced a fairly large difference between the mean amount of downslope movement, the fall mean being substantially greater than the spring mean (Table 7). Again, the difference between the amount of downslope movement is most visible in the 0.051–0.100 ppm class. The greatest residue level class (>0.101 ppm) had few occurrences in either the fall or spring applications.

The next analysis explored the effect of the different treatments on the distance of downslope movement of hexazinone. The data were sorted by site, season and distance downslope. Table 8 presents all the data, sorted by distance only. Both the means and frequency classes suggest that concentrations of hexazinone in soil water decrease with distance downslope.

TABLE 7. Mean residue values by season of application

Season	Mean residue in ppm (no. of samples)	Frequency of occurrence by residue level class				
		Below detection limit < 0.010 ppm	0.010–0.050 ppm	0.051–0.100 ppm	Greater than 0.101 ppm	Max. residue in ppm
Fall application	0.034 (116)	38%	38%	18%	6%	0.230
Spring application	0.023 (11)	52%	36%	6%	6%	0.390

TABLE 8. Mean residue values by distance downslope

Distance downslope (m)	Mean residue in ppm (no. of samples)	Frequency of occurrence by residue level class				
		Below detection limit < 0.010 ppm	0.010–0.050 ppm	0.051–0.100 ppm	Greater than 0.101 ppm	Max. residue in ppm
7	0.037 (91)	39%	36%	15%	10%	0.230
15	0.026 (86)	49%	36%	10.4%	4.6%	0.390
25	0.018 (43)	44%	44%	9.5%	2.5%	0.130

In Table 9, the data are sorted by site and distance downslope. Both the means and frequency classes support the trend that the concentrations of hexazinone residues in soil water decrease with distance downslope for both sites. The data in Table 9 also suggest that there was movement of hexazinone in greater concentrations at greater distances downslope at the Swiss Fire site than at the Gramophone Creek site. In Table 10, the data are sorted by season of application and distance downslope. The same trend is apparent as in Table 9: concentrations of hexazinone in soil water decrease with distance downslope. Table 10 also shows that the greater concentrations of hexazinone (0.051–0.100 ppm class) moved further downslope more often in the plots that received the fall application.

Analysis was also performed with only the fall 1987 and spring 1988 data (when most of the downslope movement occurred). The same trends were evident: 1) the fall application moved more than did the spring application; 2) there was more movement at the Swiss site; and 3) concentrations of residues decreased with distance downslope.

TABLE 9. Mean residue values by site and distance downslope

Site and distance downslope (m)	Mean residue in ppm (no. of samples)	Frequency of occurrence by residue level class				
		Below detection limit < 0.010 ppm	0.010–0.050 ppm	0.051–0.100 ppm	Greater than 0.101 ppm	Max. residue in ppm
Swiss Fire						
7	0.040 (45)	40%	30%	16%	14%	0.210
15	0.029 (50)	47%	31%	16%	6%	0.184
25	0.020 (21)	40%	45%	15%	0%	0.069
Gramophone Creek						
7	0.034 (48)	36%	40%	18%	6%	0.230
15	0.022 (38)	51%	43%	3%	3%	0.390
25	0.017 (24)	48%	44%	4%	4%	0.130

TABLE 10. Mean residue values by season of application and distance downslope

Season of application and distance downslope (m)	Mean residue in ppm (no. of samples)	Frequency of occurrence by residue level class				
		Below detection limit < 0.010 ppm	0.010–0.050 ppm	0.051–0.100 ppm	Greater than 0.101 ppm	Max. residue in ppm
Fall application						
7	0.043 (47)	30%	37%	24%	9%	0.220
15	0.034 (43)	40%	38%	17%	5%	0.390
25	0.021 (26)	44%	40%	12%	4%	0.130
Spring application						
7	0.031 (46)	46%	36%	7%	11%	0.230
15	0.018 (45)	57%	34%	4.5%	4.5%	0.180
25	0.014 (19)	44%	50%	6%	0%	0.069

Effect of time

A series of four "3-D" graphs were prepared to illustrate the effect of time following application of hexazinone on the amount of downslope movement (Fig. 11). These graphs show the mean hexazinone residues detected for the different distances downslope, at each of the five different sampling periods for the treatments indicated. The graphs clearly illustrate the following:

- In general, there is a reduction in concentration of residues with distance downslope from point of application.
- Most of the movement occurred in the fall of 1987 and the spring of 1988.
- Movement occurred up to a distance of 25 m on all treatments.
- The amount of movement is similar in all four site/season combinations.

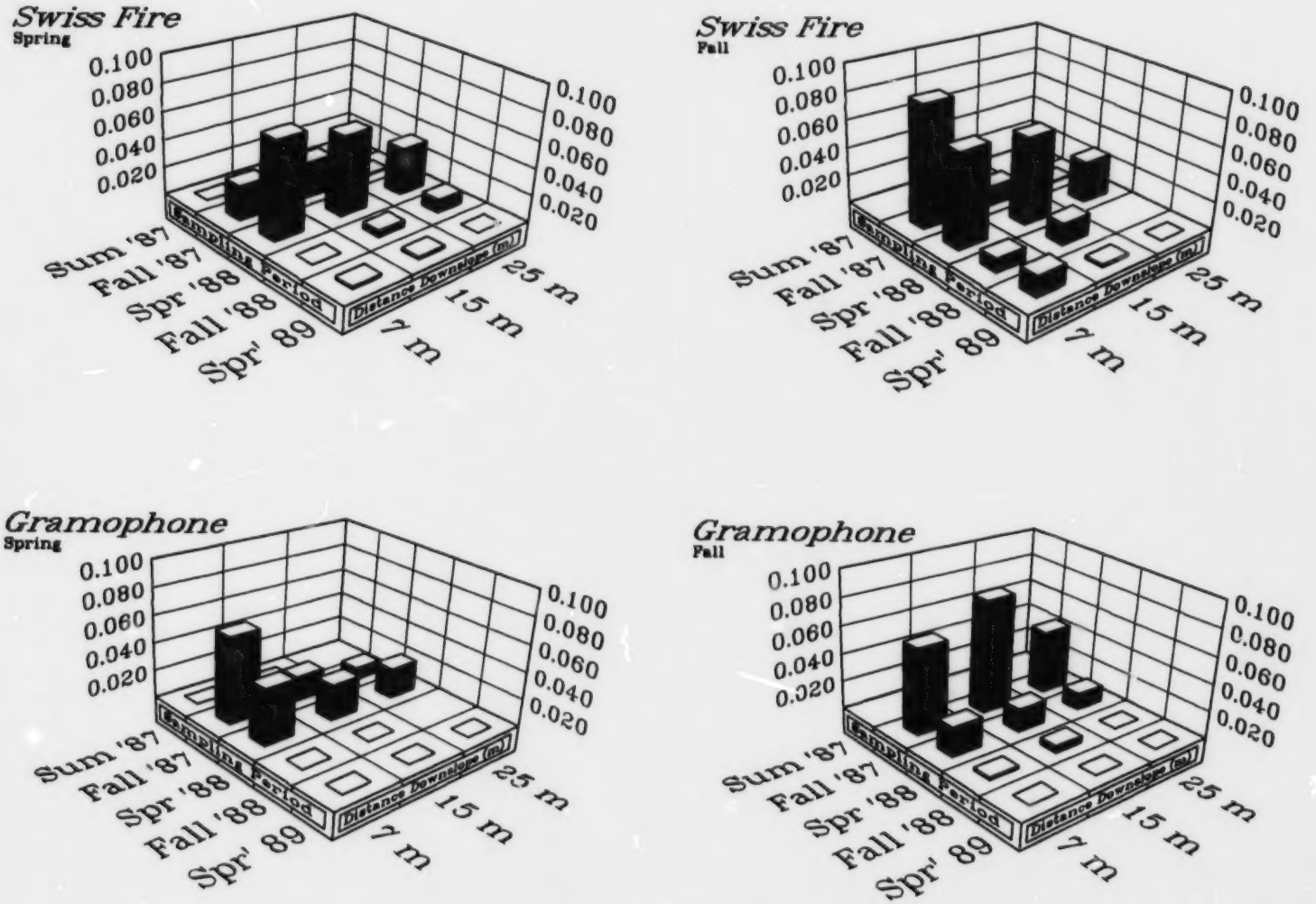

FIGURE 11. Mean hexazinone residues for the five sampling periods and three downslope distances.

Analysis of individual extreme events

It is the extreme occurrences of downslope movement that are most likely to cause downslope problems. Thus, it is essential for us to understand why and how they occur, so that we can prevent them.

Swiss Fire site: Of the 116 Swiss Fire samples analysed, the maximum residue detected was 0.210 ppm. Only six samples exceeded 0.150 ppm. Of the water samples analysed, 77% contained less than 0.050 ppm of hexazinone, 45% of which were below detection limits. Although a greater percentage of samples with residue levels higher than 0.051 ppm were recorded at the Swiss Fire site than at Gramophone Creek, all residue levels at the former were low, with no extremes occurring.

Gramophone Creek site: Of the 110 Gramophone Creek samples analysed, the maximum residue detected was 0.390 ppm. Only three other samples exceeded 0.150 ppm. Of the water samples analysed, 81% contained less than 0.050 ppm of hexazinone, 45% of which were below detection limits. The highest residue level detected (0.390 ppm) occurred on a fall-applied, 6 mL/spot treatment. The greatest amount of downslope vegetation damage to both crop and target species also occurred on this plot. The sample which contained the 0.390 ppm of hexazinone residue was collected in the fall of 1987, shortly after application of the hexazinone. The following spring and summer, damage to downslope vegetation became apparent. A continuous, narrow, sinuous pathway of damaged vegetation, 1–3 m wide, reached 30 m below the hexazinone-treated area. Along with the observable effects on rose, thimbleberry, and aspen, extensive hexazinone damage was observed on two 5 m high pine trees located 20 m downslope. It was obvious from the surface erosion and observations of overland flow that the pathway coincided with a natural depression which channelled large amounts of surface water during spring snowmelt and heavy rains. This result highlights the site-specific nature of the downslope movement of hexazinone. That is, it depends more on micro-topography and localized soil conditions than on the type of treatment used.

5.4 Influence of Soils and Climate on Downslope Movement

Organic matter, soil moisture regime, and precipitation are the three most important site characteristics that affect mobility of hexazinone. As discussed in Sections 5.1 and 5.2, these characteristics differ between the Swiss Fire and Gramophone Creek sites. The data analysed in Section 5.3 suggest that although the amount of movement was low at both sites, the movement at the Swiss Fire site was a little greater than at Gramophone Creek. Given the low amounts of organic matter present at the Swiss Fire site, we expected more downslope movement there than at the Gramophone site. However, the lesser amounts of rainfall and snowmelt that occurred at the Swiss Fire site tended to do the opposite, reducing the amount of movement. Of these two factors (i.e., organic matter and precipitation), the lower amount of organic matter at the Swiss Fire site seems to have played the dominant role. We hasten to emphasize, however, that neither of these two environmental characteristics was too high or too low to result in large amounts of downslope movement.

Although, overall, there was less downslope movement at the Gramophone site than the Swiss Fire site, the sample with the largest amount of residue was collected there. This again emphasizes the site-specific nature of the movement characteristics of this herbicide.

5.5 Summary of Movement

The following points summarize the results of the hexazinone residue analysis for both the Swiss and Gramophone sites.

- Downslope movement was, in general, very low for all treatments. Of all samples analysed, 82% contained less than 0.050 ppm of hexazinone.
- Downslope movement in soil water was predominantly sub-surface rather than over the soil surface.
- The grid spacing and the amount of chemical applied at each grid spot made no observable difference on the amount of downslope movement.
- The fall application appeared to produce, on average, more downslope movement than did the spring application.
- Most of the downslope movement occurred in the first fall and spring after application for all treatments.

- Presence of hexazinone in the soil water was almost undetectable by 12 months after treatment.
- Although only detected in very small amounts, migration of hexazinone in soil water reached 25 m downslope in all treatment combinations. This was confirmed by the sensitive plant observations.
- The amount of movement at the Swiss Fire site was slightly greater than at Gramophone Creek. This was attributed to the lesser amount of organic matter present on the Swiss Fire site.
- The amount of organic matter and the micro-topography at the spot of application seem to be the controlling factors in determining the amount of downslope movement, moreso than soil moisture, texture, or precipitation/snowmelt regime.
- No single treatment produced substantially more downslope movement than others, but all treatments did produce some downslope movement.

6 CONCLUSIONS AND RECOMMENDATIONS

Of the 226 soil water samples analysed for hexazinone residue, the highest detected amount was 0.390 ppm. Only 16 samples had residues higher than 0.100 ppm. These levels are very low relative to the 96 hr-LC_{50} (for trout) of Velpar® L, which is 875 ppm. Velpar® L's toxicity is classed as low. The amount of downslope movement detected in this experiment may not pose a toxicity problem to fish and wildlife, but the potential off-site herbicidal effects on habitat must always be considered.

The results of this experiment suggest that the period of application, the amount of organic matter, and the micro-topography at the spot of application were the most important variables that controlled the amount of downslope movement. To minimize downslope movement, an early spring treatment is more favourable than is a fall application. If the site is treated in early spring, before the flushing of plants, soil moisture is generally adequate to ensure the optimum efficacy of the herbicide Velpar® L. Furthermore, contrary to what happens in a fall application, soils tend to get drier following the spring application, which minimizes the opportunities for excessive downslope movement. To minimize downslope movement of hexazinone, sites should be avoided where excessive mineral soil has been exposed, and where there are long, continuous ruts caused by mechanical equipment.

Another factor that would help minimize movement is to limit the use of hexazinone to drier interior ecosystems and to sites where a continuous layer of at least 2–3 cm of organic matter is present. When choosing Velpar® L as a herbicide treatment, users should follow the B.C. Forest Service application guidelines. Consideration should be given to the site and the downslope values. Users should also keep in mind that although the amount of movement of hexazinone in the soil water is generally very small, the herbicide can move at least 25 m down a 15% slope. On sites with steeper slopes, lower amounts of organic matter, and wetter conditions, movement could be greater, as has been suggested by operational observations.

7 LITERATURE CITED

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APPENDIX 1. Observations of herbicide damage on plants located more than 5 m below the last point of application of Velpar® L

Treatment	Observations of damaged plants
Swiss Fire – spring application	
2 mL/spot, 4.8 kg a.i./ha	– none
4 mL/spot, 4.2 kg a.i./ha	– none
6 mL/spot, 3.6 kg a.i./ha	– minor damage of rose and false azalea to a distance of 10 m
2 mL/spot, 4.8 kg a.i./ha	– none
4 mL/spot, 4.2 kg a.i./ha	– none
6 mL/spot, 3.6 kg a.i./ha	– extensive damage on rose and aspen to a distance of 40 m
Swiss Fire – fall application	
2 mL/spot, 4.8 kg a.i./ha	– minor damage on aspen and rose to a distance of 40 m
4 mL/spot, 4.2 kg a.i./ha	– minor damage on aspen and rose to a distance of 40 m
6 mL/spot, 3.6 kg a.i./ha	– substantial damage to rose in a swath 7 m wide by 25 m long; also damage to large clumps of aspen located 10 m downslope
2 mL/spot, 4.8 kg a.i./ha	– minor damage of rose to a distance of 10 m
4 mL/spot, 4.2 kg a.i./ha	– minor damage of aspen to a distance of 50 m
6 mL/spot, 3.6 kg a.i./ha	– minor damage of aspen to a distance of 20 m
Gramophone – spring application	
2 mL/spot, 4.8 kg a.i./ha	– none
4 mL/spot, 4.2 kg a.i./ha	– minor damage of willow to a distance of 25 m
6 mL/spot, 3.6 kg a.i./ha	– minor damage of cottonwood at a distance of 15 m
2 mL/spot, 4.8 kg a.i./ha	– minor damage of aspen to a distance of 10 m
4 mL/spot, 4.2 kg a.i./ha	– minor damage of aspen to a distance of 15 m
6 mL/spot, 3.6 kg a.i./ha	– narrow path of damaged aspen up to 45 m downslope
Gramophone – fall application	
2 mL/spot, 4.8 kg a.i./ha	– none
4 mL/spot, 4.2 kg a.i./ha	– none
6 mL/spot, 3.6 kg a.i./ha	– hexazinone-damaged plants identified up to 30 m below application; downslope damage on pine, rose and alder
2 mL/spot, 4.8 kg a.i./ha	– none
4 mL/spot, 4.2 kg a.i./ha	– none; minor damage to cottonwood to a distance of 7 m
6 mL/spot, 3.6 kg a.i./ha	– none